

# **Increasing Density and Reducing Costs of Data Acquisition**

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## **Abstract**

There are a number of reasons why it is important to increase the density of data acquisition functions. Sensor fusion seeks to integrate large numbers of sensors into a decision network. Addition of health monitoring functions may incur additional sensor requirements. But at the same time, it is important to reduce the per-channel costs of data acquisition systems. Often the most significant cost is the management of data acquisition networks, which incurs substantial costs associated with transducer installation, configuration, calibration, and maintenance. Alternatives that lower the cost of the transducer system and reduce the data acquisition system channel count will directly impact initial system costs. Other techniques that affect maintenance and operating costs will contribute to reducing life-cycle costs.

This paper describes work undertaken to explore alternative architectures for lowering the cost per transducer function using a MEMS-based accelerometer as the model.

## **Introduction**

Continued improvements in transducer, analog-to-digital conversion, and computer technologies combine to offer opportunities to increase both the density of measurements and their bandwidth. While some costs continue to decrease; for example, computing costs, others stay flat or rise. For installations with numerous transducers that must be configured—or reconfigured—calibrated, and maintained, the associated personnel costs can be very high. Similarly, the addition of new sensors to a data acquisition environment may incur high per-channel costs. Work undertaken with NASA<sup>1</sup> sought to explore alternatives for reducing per-channel data acquisition costs.

## **Case Study: Multi-axis MEMS Accelerometer**

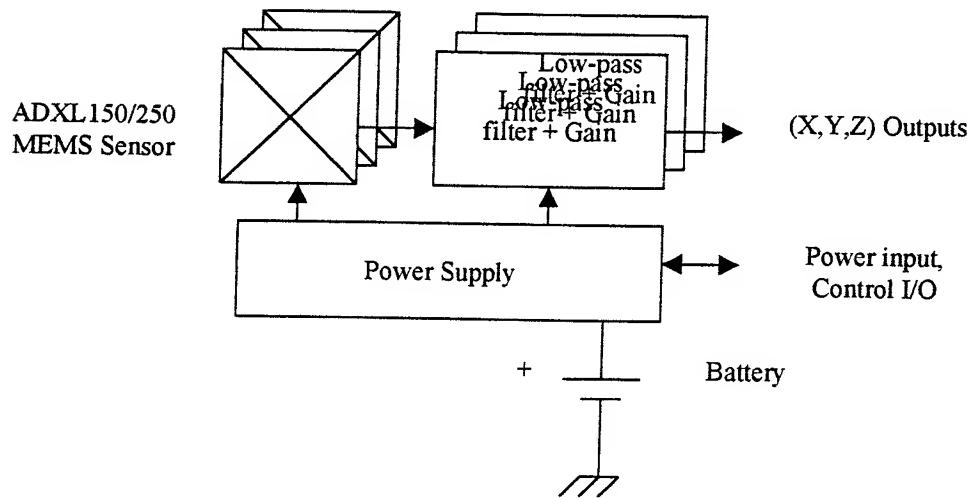
Determination of acceleration is important for a number of physical measurements. For example, recent tests of a 650k hybrid rocket engine required measurements of multiple site accelerations for reconciliation of a building structural model. The objective

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<sup>1</sup> The opinions expressed herein are solely those of the authors and do not represent NASA positions or policy.

was to compare response predictions to measurements of dynamic loading from the nearby horizontal engine test. Traditional accelerometers usually employ a piezoelectric structure; mechanical motion results in crystal deformation with attendant changes in charge,  $Q$  (Coulombs). Signal conditioning consists of a charge amplifier to convert the  $dQ/dt$  to a voltage for data acquisition. This class of accelerometers is expensive and requires high-cost cabling and signal conditioning. Recently, alternative micro-electromechanical systems (MEMS) technologies have been used to manufacture accelerometers. Intended for high-volume applications such as automotive crash sensors, these MEMS sensors include transducer elements and the necessary signal conditioning electronics integrated together on a single integrated circuit (IC). This section describes some of the developmental process undertaken to determine the feasibility of producing low-cost MEMS-based accelerometer systems suitable for measurements in support of building structural response studies and similar low-bandwidth applications.

A feasibility study was undertaken to produce high channel density, low-cost MEMS-based accelerometer systems. Targeted for structural applications in a propulsion test environment, initial goals of the project included development of compact, low-cost 3-axis acceleration systems based on commercial off-the-shelf (COTS) MEMS. Fig. 1 shows the block diagram for the MEMS-based multi-axis accelerometer system.



**Figure 1.** Block diagram of MEMS-based accelerometer system. Up to three channels can be supported. Provision for battery operation is included.

**General features of MEMS accelerometers.** MEMS-based accelerometers are manufactured by a number of vendors [1-3]. The core transducer technology is some form of capacitor structure. Capacitance is a function of physical displacement resulting from inertial response of a movable electrode in response to acceleration. Advantages of the MEMS approach include the ability to fabricate high-sensitivity devices that include signal conditioning electronics.

A MEMS accelerometer manufactured by Analog Devices was selected for evaluation. Analog devices makes a family of MEMS accelerometers including the ADXL150 (single-axis) and ADXL250 (dual-axis) units, which provide sensing of up to

$\pm 50\text{-}g$ . Combining these two units together in a package makes it possible to implement a 3-axis accelerometer. Another sensor available from Analog Devices is the ADXL202, which provides  $\pm 2\text{-}g$  sensing. Silicon Designs offers the MDI 1010, which is available in ranges from  $\pm 5\text{-}200\text{-}g$ . Motorola also makes MEMS-based accelerometers.

**Theory of operation.** The accelerometer system depicted in Fig. 1 consists of three major subsystems. A MEMS accelerometer produces a voltage proportional to acceleration. The sensor output is further filtered and amplified, and an on-board voltage regulator provides power supply conditioning.

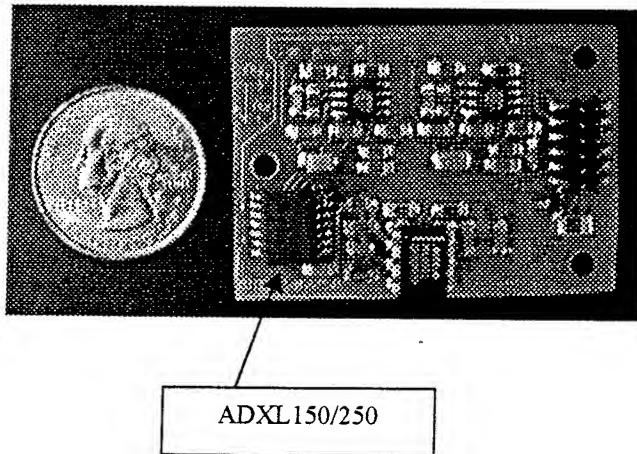
- MEMS accelerometer. The MEMS-based accelerometers are monolithic circuits made by Analog Devices. The ADXL150 provides single-axis, and the ADXL250 provides two axes of acceleration detection. The full-scale range that the devices can support are  $\pm 50\text{-}g$ . For full three-axis support, both an ADXL250 and an ADXL150 mounted orthogonal to the ADXL250 are required. A self-test feature allows simple go-no go testing of the accelerometer. Application of a test voltage causes the MEMS structure to displace producing a near full-scale output.
- Low-pass filter + gain. The MEMS sensor has a bandwidth of 1 kHz and produces a nominal output of 38 mV/g. The output noise of the sensor is  $1\text{ mg}/\sqrt{\text{Hz}}$ ; reducing the bandwidth provides an attendant improvement in signal-to-noise ratio (SNR) proportional to the square root of the bandwidth reduction. For example, reducing the bandwidth from 1 kHz to 100 Hz would result in a reduction in the output voltage noise by a factor of  $1/\sqrt{10} = 0.317$ . Similarly, if the maximum sensor acceleration range of  $\pm 50\text{-}g$  is not needed, additional gain can be used to increase the scale factor. The disadvantage is that the accelerometer system output will saturate at a lower total  $g$  if out-of-range accelerations are encountered.
- Power supply. A choice of battery or external voltage source can be used to drive the system. An on-board, low-dropout voltage regulator with remote shutdown capability provides the 5-Vdc required by the MEMS sensor and the external filtering and gain components.

**Design philosophy.** The design goals for the evaluation module included:

- Full 3-axis acceleration measurement.
- Maximum dynamic range of  $\pm 10\text{-}g$ .
- Bandwidth limit of 100 Hz.
- Dual power source capability: local battery and/or remote power supply.
- Hard-wired, voltage-level interface.

The design was implemented using predominantly surface-mount technology (SMT) in order to provide the smallest package size practical. Driven by the fact that the ADXL150/250 are only available as surface mount devices (SMD), the decision was made to complete the design as SMT. All devices selected for the design are available in SMD configurations; however, the lead times on the voltage regulator IC are 17 weeks, so a dual inline package (DIP) was used instead because they were available as samples. A printed circuit board (PCB) was developed to host the MEMS sensors with additional

support electronics for filtering, gain, and power conditioning. A single layout supports both the ADXL150 and the ADXL250; implementation of either of the two sensors with or without power supply is handled by component selection during assembly. A second version was also designed with an SMD layout for the voltage regulator. Both PCBs were fabricated to allow both SMD and through-hole technology components to be used as available. Fig. 2 is a photograph of the Rev 1.0 prototype.



**Fig. 2.** Photograph of Rev 1.0 MEMS-based prototype.

Packaging. Limited packaging design was performed for the Rev 1.0 prototype.

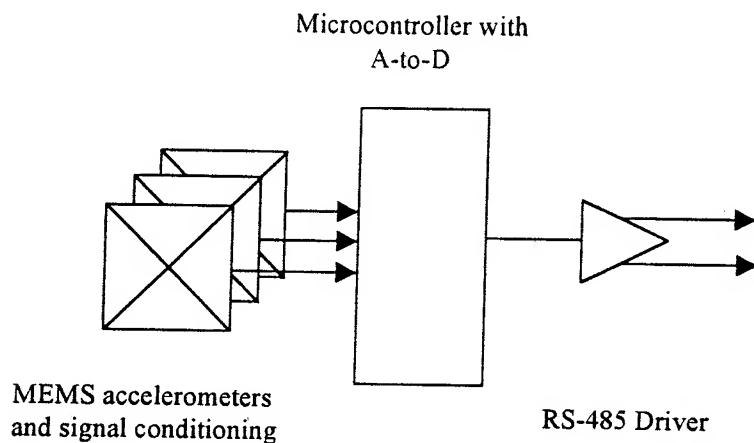
Interface. The Rev 1.0 design produces buffered analog voltage outputs; these must be interfaced to a data acquisition system at a cost of three data acquisition channels for all three acceleration axes.

Results and discussion. The Rev 1.0 prototype demonstrated that a 3-axis MEMS-based accelerometer system is a viable alternative to other technologies. In small quantities, the devices have an estimated cost of \$500.00; if these were scaled to commercial quantities, the costs would be significantly reduced. However, the additional goals of reducing the total data acquisition system costs were not achieved with the first generation device.

Follow-on work. A second revision of the accelerometer has been developed. It specifically focuses on reducing the per-channel data acquisition costs. These costs can range up to \$2,000 per channel for a fixed installation using standalone signal conditioning units, such as found in the rocket engine test stands. For applications involving direct interface to PC-based data acquisition cards, the costs are typically in the range of \$100 per channel. The primary goal of Rev 2.0 was to reduce the per-channel system costs. This was achieved as depicted in Fig. 3.

The original 3-axis design was complemented with an onboard microcontroller offering an on-chip 12-bit analog-to-digital converter. The microcontroller performs continuous conversions outputting acceleration data as a comma-separated variable bit stream. An RS-485 line driver provides long-haul drive capability; the differential format

helps increase noise immunity and decrease the bit error rate. At the receiving end, an RS-485 to RS-232 converter makes the bit stream compatible with a standard PC



**Fig. 3.** Rev 2.0 accelerometer incorporates A-to-D conversion and RS-485 line driver.

serial port. Application code was written in Lab-View in order to process and display the data.

**Results and discussion.** The relocation of the A-to-D converter function with multiplexing onto the device provides immediate system cost reductions. The exchange of a digital interface for the analog voltage interface means that the transducer package can be located far away from the data acquisition system computer. While RS-485 can support much higher bit rates, a relatively low-speed 33.8 kbps was used.

### Future Development

The results of the work to date have demonstrated the feasibility of using MEMS-based accelerometers for many low bandwidth applications. Enhancements to the system have also shown the real possibility of significantly reducing the per-channel data acquisition costs. However, there are additional improvements that can be made to further address operations and maintenance issues as part of reducing life-cycle costs.

Future development can include co-locating a transducer electronic data sheet (TEDS, IEEE 1451). This would reduce the costs associated with transducer configuration thereby reducing the manpower needed to configure and re-configure transducers in a data acquisition database.

Other possible enhancements include the development of wireless versions. This would allow rapid deployment in time-sensitive applications. However, a significant disadvantage of wireless techniques is the amount of power required to support the system. Short-term application requirements may well be met with a battery-operated system; long-term installations would require fixed power sources.

Finally, the addition of the on-board data acquisition function means that even more transducers could be hosted by one node. This would result in only incremental cost increases but could have significant impacts on the density of sensor signals. The increased number and type of sensor data would be valuable for improved sensor fusion and intelligent health monitoring applications [4].

## References

- [1] Analog Devices, Inc. One Technology Way, P.O. Box 9106, Norwood, MA 02062-9106, (617) 329-4700. [www.analog.com](http://www.analog.com).
- [2] Silicon Designs Inc. 1445-NW Mall Street, Issaquah, WA 98027-5344, (425) 391-8329. [www.silicondesigns.com](http://www.silicondesigns.com).
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